corresponding to relativistic oxygen. The δ-ray calibration was established as follows:

(a) High energy α-particles (approximately 20 Bev per nucleon) resulting from a C-collision, were δ-ray counted. Minimum ionization tracks were also δ-ray counted. Since for relativistic particles:

$$\delta_Z = Z^2 a + b,$$

where "a" is a constant and "b" the δ-ray density due to random electrons, both "a" and "b" can be determined.

(b) Because of the difficulty in maintaining the same criterion for δ-ray counting when counting a track of minimum ionization the method described above is not extremely reliable. Therefore particles which were identified as oxygen in the insensitive plates were δ-ray counted in the sensitive plates. The results were consistent with the δ-ray calibration from relativistic protons and α-particles.

Using this calibration we obtain in the primary flux a strong peak corresponding to the CNO group and very few particles of charge $2<Z<6$ in agreement with our previous results.[3]

The calibration curve for the C-2 and NTA emulsions is shown in Fig. 15. It will be noted that the curves reach saturation at very low grain densities. We presume this could be avoided by using less sensitive emulsions and less underdevelopment. For steep heavy tracks δ-ray counts became unreliable and grain counts were used to determine charge.

Corresponding results were obtained with the White Sands charge calibration.

PHYSICAL REVIEW VOLUME 85, NUMBER 2 JANUARY 15, 1952

The Variation of Intensity of Fast Cosmic-Ray Neutrons with Altitude

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(Received August 29, 1951)

Using BF_3 proportional counters, containing boron enriched in B^{10}, imbedded in a paraffin block $15\times15\times17$ inches, as a moderator of fast neutrons, the intensity of such neutrons generated in the atmosphere by cosmic rays has been measured at a number of altitudes between 5000 and 13,000 feet above sea level. These locations were all along the same geomagnetic latitude of 20° 32′ N in Kashmir. The intensity thus measured was found to increase approximately in an exponential manner with decreasing atmospheric pressure under the conditions of the experiments, in general agreement with observations made by other investigators in the free atmosphere, giving an attenuation length in the atmosphere of 128 g/cm^2.

I. INTRODUCTION

CONSIDERABLE interest has been shown in the last decade in the neutron component of cosmic radiation with attention focused chiefly on the slow neutrons in the atmosphere. The slow neutrons offer the advantage of detection by relatively simple means, such as BF_3 counter tubes, which makes possible the use of equipment of light weight suitable even for free balloon flights. This accounts in part for the numerous investigations of their variation in intensity with altitude.

Detectors of fast neutrons, on the other hand, are usually heavy and bulky, since to date the most satisfactory method of detecting these neutrons is to moderate them in some medium, such as paraffin, and then to detect them as slow neutrons with BF_3 counters imbedded in the moderator. Such devices cannot be carried aloft readily by balloons. Consequently about the only convenient way of making measurements of fast neutrons generated in the atmosphere at various levels is either to transport the equipment to various heights on the surface of the earth or to use airplanes. Observations with airplanes suffer from an inability to maintain even an approximately constant position laterally and vertically for the relatively long time required to obtain measurements of a statistical accuracy of the order of one percent. Also the use of planes for this purpose is expensive. Since fast neutrons are presumably a direct product of that type of interaction between the cosmic radiation and atomic nuclei which leads to nuclear disintegration, it is reasonable to suppose that the study of fast neutrons in the atmosphere would give more direct information regarding the nature of this process than is obtained from data regarding slow neutrons.

These considerations led the authors to attempt to obtain information regarding the variation of intensity of fast neutrons in the atmosphere over a limited range of altitudes at some elevated location on the surface of the earth. The region selected for these trials is in Kashmir where altitudes between 5000 and 13,000 feet are accessible lying along the same geomagnetic latitude 20° 32′ N. Also adequate manpower at low cost is available there to carry the relatively heavy equipment up over the snow fields and rough terrain in the steep

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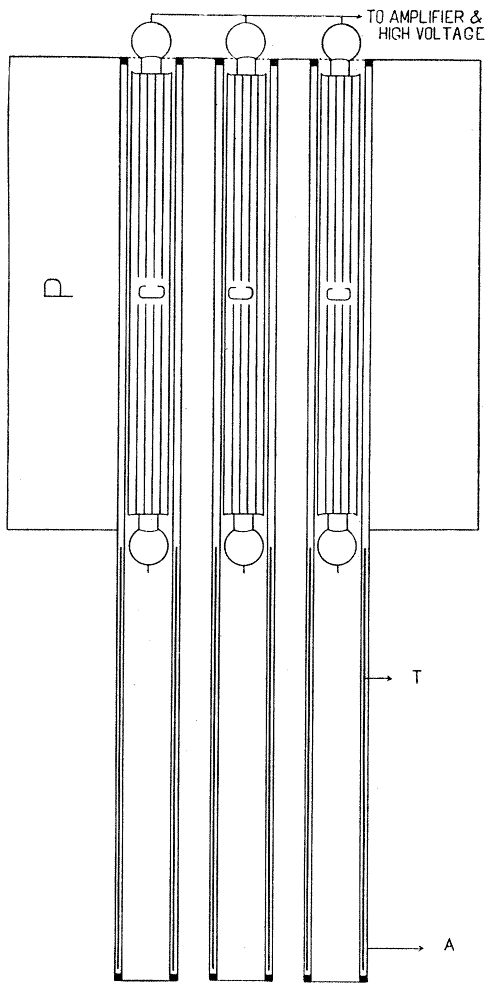

FIG. 1. Plan of detector block; *P*—Paraffin block; *C, C, C*—BF_3 proportional counters; *T*—Tubular cadmium shields; *A*—Aluminum guide tubes which support cadmium shields when withdrawn.

ascents encountered. This paper describes the equipment, methods of observation, and results obtained on such an expedition in Kashmir from May to August, 1951. Two separate ascents were made in the Himalayan Mountains from Srinagar, the capital of Kashmir. One was through Tangmarg, Gulmarg, and Khellanmarg to Alapathar Lake. The other went through Pahalgam, Goshangan, and Lower Katar Nag to Katar Nag near the Kolahoi Glacier. The maximum altitude attained in each case was about 13,000 feet.

II. EXPERIMENTAL EQUIPMENT

Although it has been usual to employ battery-operated equipment in making cosmic-ray studies in the field, it was decided in this case to use a more or less conventional laboratory amplifier and scaler designed to operate from a 110-volt ac supply. This procedure permitted the use of equipment which had been tested over long periods in the laboratory and could therefore be expected to be thoroughly reliable. On the expedition, this apparatus was operated from a gasoline-driven generator giving 110 volts at 60 cycles and capable of delivering 500 watts. The outfit selected had a centrifugal governor on the engine, permitting the voltage to be adjusted quite accurately and also holding this voltage at a remarkably constant value under the constant load represented by the electronic equipment.

Three BF_3 proportional counters were used to detect the moderated neutrons. These counter tubes were made of brass with Kovar seals in each end and were 14 inches long and 1.5 inches in external diameter. They were of commercial manufacture, and the boron used in the filling mixture was about 98 percent B^{10}. The pressure of the filling gas was about 45 cm and the operating voltage extended from 2700 to 2900 volts with less than ± 1 percent change in counting rate. This range was nearly identical for each tube. These counter tubes were mounted in a paraffin block 15 by 15 by 17 inches, with centers separated by 3 inches as shown in Fig. 1. They were supported inside aluminum tubes passing through the paraffin block and extending to one side a distance slightly greater than the length of the counter tubes. These aluminum tubes served as guides for tubular cadmium shields which could be slid over the counter tubes to exclude thermal neutrons and thus measure the background of the counters. This procedure was also useful in checking the proper operation of the equipment. Any defects which might cause spurious counts could be readily detected, if present, with these shields covering the counter tubes. In this way leakage of high voltage over insulation or corona discharge would have been revealed. Little trouble of this kind was encountered. These cadmium shields cut out all but about 2 percent of the slow neutrons reaching the counter tubes. This was determined by measurements with a Ra-Be α-type source, containing about 100 mg of radium. Thus the shields reduced the normal counting rate to a correspondingly low value. The actual background of the counter tubes, which should have the same average value throughout the experiments, was taken as the average counting rate at sea-level with the tubes covered with cadmium. This was found to be 0.15 ± 0.02 count per minute under the conditions maintained throughout the observations. The measured background count increased with altitude, roughly proportional to the increase in total neutron count. This slight increase was attributed to the previously mentioned leakage of neutrons past the cadmium shields, rather than to a direct effect on the counter tubes of some component of the cosmic radiation. The maximum background rate at the higher altitudes was approximately 0.65 count per minute. It is to be noted that this detector for fast neutrons responded to those generated in the paraffin block and in the earth nearby, as well as in the surrounding atmosphere.

The high voltage for operating the proportional counter tubes was obtained from the rectifier circuit in the commercial scaler used for recording the counts. This circuit delivered a maximum of 2500 volts dc. Since the tubes required 2800 volts, a 300-volt miniature battery was inserted in the high voltage line to the counter tubes. The pulses from these three tubes, connected in parallel, were amplified by a Jordan and Bell amplifier,[1] and fed to the scaler. This amplifier contained a discriminator circuit which was adjusted in combination with the gain control to give most satisfactory operation. Once these conditions were ascertained, by tests in the laboratory with a neutron source, neither control was changed throughout the experiments. It was found desirable to reject about 10 percent of the actual neutron-induced pulses in order to make sure that spurious pulses were not recorded by the scaler. This small percentage of the neutron pulses was found to have heights only slightly greater than the noise level of the amplifier, so that it was impractical to attempt to record all pulses. Since the same fraction was rejected for all observations by a pulse-height discriminator attached to an appropriate stage of the amplifier, this procedure could not be expected to interfere seriously with the measured relative values of neutron intensity. Each component was crated in a wooden box, with adequate padding, to be carried by coolies from one experimental site to another.

III. METHOD OF OBSERVATION

It was decided at the start of the series of measurements to arrange the components in a definite way which was maintained throughout the observations. The detector block was placed directly on the ground, the amplifier housed in a heavy steel cabinet on top of this block with the scaler resting on the amplifier cabinet. This arrangement required a minimum of ground space in the tent and was convenient for operation. To protect the apparatus from direct sunlight and from rain, it was sheltered in a small tent which was always placed at some little distance from buildings or other obstructions, such as banks of snow or walls of rock. Tests made during the expedition revealed that it was important to adhere rigidly to the definite arrangement of parts and to avoid proximity to obstructions. Any changes in arrangement or placing the equipment near obstructions caused changes in the apparent efficiency of the detector.

When in operation, the gasoline-driven generator was monitored for output voltage at frequent intervals. However, the governor on the engine was so efficient that this was in general only a precautionary measure. Drifts of voltage after the initial warm-up period were rare and momentary fluctuations of voltage did not exceed ± 1 percent in normal operation.

Readings of the scaler and of a large calibrated aneroid barometer, compensated for the effect of temperature changes, were made every hour during observation periods. The barometric pressure assigned to a given point was the average of these hourly readings over the time required to accumulate at least 10,000 neutron counts. Usually there was little change in the barometric readings for a given set of observations. Measurements with the cadmium shields over the counter tubes were made at intervals to check the operation of the circuits. Since the counting rates varied from about 4 per minute at 5000 feet to roughly 18 per minute at 13,000 feet, the time required for a complete set of observations ranged from about 60 to 15 hours.

While at Gulmarg, advantage was taken of the opportunity to observe the effect of an additional slab of paraffin, 4 inches thick and of an area equal to that of one side of the detector block, when this slab was applied to different sides of the block. The effect in all cases was to reduce the counting rate by about 10 percent, with little if any indication of any directional effects in the neutron flux. Furthermore, when the equipment was brought inside a frame house, a similar reduction in the apparent neutron intensity was noted. This confirms the suggestion, made by Cocconi,[2] that the neutrons generated in the atmosphere have energies of less than 10 Mev. Otherwise this additional paraffin might have been expected to increase the efficiency of the detector block.

IV. EFFECT OF TEMPERATURE CHANGES

Temperatures of the equipment changed quite radically during a 24-hour period of observation. When the sun was shining the temperature of the interior of the tent rose to about 90°F in the early afternoon, and it fell to about 35° to 40°F at most sites in the early hours of morning. It was impracticable to measure the temperatures of the detector block under field conditions, and it was hoped that the effect of changes in temperature, if these were marked, would average out over the relatively long observation period at each site. It was further suspected that any effect of temperature change was quite small. This was deduced from comparing hourly counting rates taken at various times during the day which were found to be quite constant, within limits of statistical accuracy.

To answer more completely the question of the effect of temperature change, a metal box was constructed on returning to Aligarh University in which the detector block was placed. A surrounding wooden box was used to retain a layer of ice in contact with the metal box, and counting rates with a Ra-Be neutron source were observed at different temperatures measured by a thermometer imbedded in the paraffin of the detector block. This study of the effect of change of temperature was complicated by the fact that only a relatively

[1] W. H. Jordan and P. R. Bell, Rev. Sci. Instr. 18, 703 (1948).

[2] V. T. Cocconi, Phys. Rev. 74, 226 (1948).

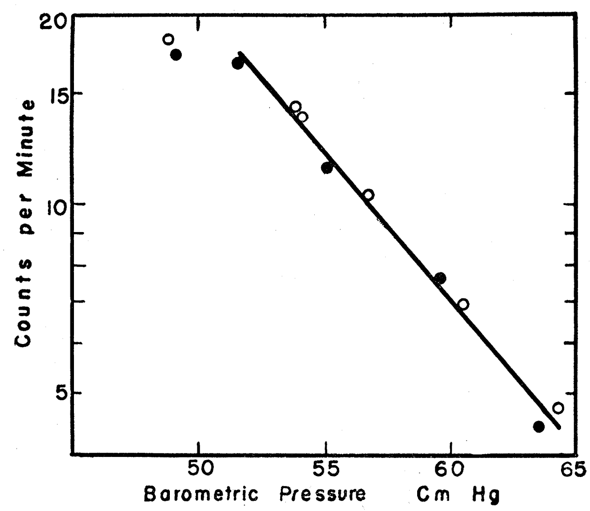

FIG. 2. Intensity of fast cosmic-ray neutrons *vs* barometric pressure. Open circles taken on Srinagar, Tangmarg, Gulmarg, Khellanmarg, and Alapathar Lake ascent. Solid circles taken on Srinagar, Pahalgam, Goshangan, Lower Katar Nag, and Katar Nag ascent.

strong source of neutrons (100 mg Ra) was available for the test, requiring the source to be outside the cooling arrangement. Under these conditions the neutron counting rate was dependent on the density of the layer of ice used for cooling. When precautions were taken to keep the same amount of ice in this layer, it was found that in the range of 13.1°C to 35.9°C the counting rate was not noticeably affected by differences of temperature. In view of the fact that no marked effect of temperature would be predicted for this detector block, this was regarded as satisfactory proof of the absence of such effects within the one percent accuracy aimed for in the measurement of the fast cosmic-ray neutrons.

V. EXPERIMENTAL RESULTS

The counting rates, corrected for the small background rate, obtained at nine different sites in the two ascents are plotted semilogarithmically in Fig. 2, against the corresponding average barometric pressure. The observations, with the exception of one point for each ascent, follow an exponential curve with a surprisingly small scattering of points considering the nature of the measurements and the conditions under which they were taken. As has been indicated, the two ascents were in localities about 80 miles apart and about a month intervened between these series of measurements. The peculiar fall of intensity at the uppermost point is evident in each series and therefore might be regarded as real. This deviation is difficult to explain on the basis of any defect in the equipment since leakage of voltage over insulators or corona discharge in the reduced air pressure would almost certainly be revealed by a marked increase in the counting rate. Apart from these two points, the points lie closely along a straight line with a slope corresponding to an attenuation length in the atmosphere of 128 g/cm^2 which is approximately that quoted by Rossi[3] for cosmic-ray bursts and close to that for stars and penetrating showers. It is considerably less than the value for slow neutrons. This is to be expected since the processes recorded as bursts and stars are assumed to give rise to the fast neutrons in the atmosphere. In general it can be concluded that measurements made at various altitudes on the earth, as described in this paper, give results quite similar to those obtained in the free atmosphere with balloons or planes under more convenient conditions of observation.

If measurements of the rate of production of fast neutrons in the atmosphere prove to have value in exploring the nuclear reactions which accompany cosmic radiation, and in particular the study of the variation of this rate with altitude, the present experiments may serve as a preliminary guide in planning similar observations in the future, where the experiments are to be performed on the surface of the earth. They may also be helpful in calling attention to some of the precautions to be taken in such studies and serve to emphasize the necessity for observations of relatively high statistical accuracy. Obviously some of the scattering of the points in Fig. 2 must be attributed to the actual fluctuation of intensity of the cosmic radiation itself. It is not easy to see how such effects can be avoided or their influence on the data compensated except by extending observations over much longer periods than was possible in the present experiments.

VI. ACKNOWLEDGMENT

In conclusion the authors wish to acknowledge the support of the Fulbright Program which made it possible for one of us (L.F.C.) to come to India, and to thank Dr. E. U. Condon, Director of the National Bureau of Standards, for permission to participate in this work. We are also indebted to Aligarh University for financial aid and appreciate in particular the interest which the Vice-Chancellor, Dr. Zakir Husain, has taken in this work. This work was greatly facilitated by the cooperation of various officials of the Kashmir Government and by the aid of several graduate students and staff members of the Department of Physics at Aligarh University, who gave time from their summer vacation to help in taking the observations under what were often difficult conditions.

[3] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).